

29 DEC 1987

## Appendix E

## MAINTAINABILITY

**Overview of Maintainability** MIL-STD-721C defines Maintainability (MTTR) as the measure of the ability of an item to be retained in or restored to a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources at each prescribed level of maintenance and repair. Simply stated, maintainability is a design characteristic which measures the capacity of a design to reduce system/equipment downtime which is required for maintenance actions. Maintenance actions are grouped into two categories:

1. Preventive or scheduled maintenance tasks implemented for an item to be "retained in" a specified condition
2. Corrective or unscheduled maintenance tasks required for an item to be "restored to" a specified condition.

System maintainability is a significant determinant of the operational availability of the system. Maintainability (MTTR) design characteristics have direct impact on the other elements of  $A_0$ , reliability (MTBF) and supportability (MLDT). System reliability is impacted by the preventive maintenance action program which is intended to reduce the risk of equipment wearout and failure. System supportability is directly impacted by maintainability design characteristics that determine the requirements for maintenance manning level, training, tools, and spare parts requirements. The Program Manager must be aware that although maintainability is usually measured only in terms of the MTTR portion of equipment downtime, maintainability design characteristics and ultimately the system Maintenance Plan, influence many of the logistic support requirements for the system.

**Maintainability Trade-Off Analysis** The Program Manager must ensure that adequate analysis is performed to allow selection of maintainability design characteristics balanced with system requirements for reliability and logistic support. These design trade-off analyses are conducted as an iterative process, but with a definite order of precedence. Reliability/maintainability trade-off analyses are performed initially to determine equipment design characteristics and configuration. Maintainability/supportability analyses are then conducted to determine the logistic support system that is required to meet equipment design characteristics. Because the Program Manager's primary measure of effectiveness is system  $A_0$  these design trade-off analyses are iterated to determine the effect of each design action on the  $A_0$  components of reliability, maintainability and supportability.

**Overview of Reliability/Maintainability Trade-Off Analyses** Maintainability trade-offs are conducted to achieve an optimum balance, within mission and resource requirements, between the frequency of failures and the down time and resources required for maintenance. Usually, reliability improvements have an associated cost increase. The Program Manager determines, within specific mission requirements for  $A_0$  the most cost-effective mix of inherent design reliability and maintenance requirements. The procedures for reliability/maintainability design and trade-off analyses are significantly different between preventive maintenance actions and corrective maintenance actions.

Preventive maintenance actions are performed to enhance overall system reliability and reduce the risk of failure. The objective of preventive maintenance analysis is to

29 DEC 1987

determine the optimum resource allocation for scheduled maintenance against the reliability improvement which is gained. The analysis of preventive maintenance employs a standardized analytical technique, called Reliability Centered Maintenance (RCM) analysis. RCM analysis is a decision logic process that identifies those maintenance actions that improve system reliability and are cost effective. The selection of scheduled maintenance actions is initially constrained by fixed requirements for system safety and mission success. Scheduled maintenance must be performed on any item whose loss of function or mode of failure could have safety consequences. If preventive tasks cannot reduce the risk of such failures to an acceptable level, the item is redesigned to alter its failure consequences. Scheduled maintenance is also required for any item whose functional failure will not be evident to the operator, and therefore cannot be reported for corrective maintenance action. In all other cases in which the consequences of failure are either cost increase or degradation of functions, scheduled tasks directed at preventing failures are justified on the grounds of cost or mission enhancement. An RCM analysis program leading to the identification of all preventive maintenance requirements includes only those tasks that satisfy the criteria for both applicability and effectiveness. The applicability of a task is determined by the technical characteristics of the item, and its effectiveness is defined in terms of failure prevention and reliability improvement.

The objective of reliability/maintainability trade-off analyses, which are conducted for corrective maintenance actions, is to determine a balance between resource allocation for reliability improvement, cost of maintenance, and the penalty of equipment downtime. These analyses measure the resources required to perform the maintenance action and to eliminate or reduce the frequency of the failure mode in the equipment design. In the early design phase, before detailed results are available from the evaluation of logistic support requirements, time is utilized as the primary measure of reliability and maintainability. Reliability is measured in terms of Mean Time Between Failure (MTBF) and maintainability is measured as Mean Time To Repair (MTTR). The basic relationship for reliability/maintainability trade-off is based on the inherent availability ( $A_i$ ) of the system:

$$A_i = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

The Program Manager must realize that this level of reliability/maintainability trade-off analysis does not provide assurance that the system will achieve an optimum level of operational availability. This stage of analysis ignores Mean Logistic Down Time (MLDT), which may be the most significant factor in achievement of operational availability.

Corrective maintenance analysis has two objectives. First, the equipment design is assessed in order to evaluate its reliability and maintainability characteristics. In this trade-off analysis, undesirable characteristics are identified as design problems and fed back to the design team for correction or improvement. Second, during maintainability/logistic trade-off analysis, tentative maintenance levels for each maintenance task, and tentative support equipment requirements are identified. Corrective maintenance requirements are then subjected to both task and skills analysis, and time-line analysis. The Program Manager should understand that this grouping of trade-off analyses is not always clear or required. During the reliability/maintainability trade-off analysis the practicality of logistic support must be considered, in addition to MTBF and MTTR. Logistic support requirements for tools, spares and training will be determined by the equipment design characteristics which are established to achieve the values of MTBF and MTTR. Therefore, this section will describe those corrective maintenance analyses which primarily evaluate MTTR, but must also consider logistic practicality. The following section will

29 DEC 1987

describe those analyses which are conducted primarily for trade-off analysis of maintainability/supportability.

### ANALYSIS OF PREVENTIVE MAINTENANCE

Objective of RCM RCM employs an established method of analysis to determine the specific preventive maintenance actions that actually improve system and equipment reliability. The RCM concept was established by the commercial airline industry in the early 1960's as a tool for development of an effective preventive maintenance program. The industry found that many preventive maintenance actions had no effect on the actual failure rate of equipments, and may even have been detrimental, due to maintenance errors and maintenance induced failures. It had always been the underlying assumption of aircraft maintenance theory that there is a fundamental cause and effect relationship between scheduled maintenance and operating reliability. This assumption was based on the intuitive belief that because mechanical parts wear out, the reliability of any equipment was directly related to operating age. It followed that the more frequently equipment was overhauled, the better protected it was against the likelihood of failure. The only decision to be made for scheduled maintenance was in determining the equipment age limit for maintenance which was necessary to assure reliable operation. The RCM concept allowed the application of more decision factors than time in the development of an effective scheduled maintenance program.

The objective of RCM is to determine the minimum set of preventive maintenance tasks which will allow the equipment to achieve inherent reliability at minimum costs. Each scheduled maintenance task in an RCM program is generated for an identifiable and explicit reason. The consequences of each failure possibility are evaluated, and the failures are then classified according to the severity of their consequences. Proposed tasks for all significant items which would hinder operating safety or preclude mission success are then evaluated according to specific criteria of applicability and effectiveness. The resulting preventive maintenance program includes all the tasks necessary to protect operating reliability, and only the tasks that will accomplish this objective.

RCM Analysis Process The basic process to develop preventive maintenance requirements using RCM techniques is presented in MIL-HDBK-266 (NAVAIR) and the NAVSEA RCM Handbook. Differences in the application of RCM to systems, structures and various types of equipment are covered in these documents. To complete the RCM analysis process, the following information must be derived.

- a determination of significant items
- a method of partitioning the system to a workable level
- a Failure Mode and Effects Analysis (FMEA)
- an evaluation of failure consequences
- an evaluation of proposed maintenance tasks.

The procedures for performing a Failure Mode, Effects, and Criticality Analysis (FMECA) are described in Appendix D and delineated in MIL-STD-1629A. This section describes the RCM logic, including the evaluation of failure consequences and proposed maintenance tasks. To determine significant items and failure modes and effects, it is necessary to refer to the standards listed above prior to beginning the RCM logic process.

29 DEC 1987

The preventive maintenance requirements, as determined by the RCM logic, can be input into the maintenance planning and logistic support analysis process. Figure E-1 shows the decision diagram through which the RCM analysis is accomplished. The key to the complete process for determining preventive maintenance requirements is the use of the RCM decision diagram.

## **RCM ELEMENTS**

**RCM decision diagram** Figure E-1 depicts a RCM decision diagram. Questions one through three determine the consequences of failure for every failure mode of each significant item. Next, depending on the consequence of failure, the proposed maintenance tasks to satisfy each failure mode are evaluated for applicability and effectiveness. This logic diagram generally provides a clear path to follow. In cases where a yes or no answer is not evident, a default logic is provided. The default logic specifies which path to follow in cases of uncertainty.

**Default decision logic** The information to be channeled into RCM decisions requires analysis under two different sets of conditions: (1) the development of an initial maintenance program on the basis of limited information; and (2) modification of these initial requirements as information becomes available from operating experience. As information accumulates, it becomes easier to make decisions. In a new acquisition program, however, there are many areas in which there is insufficient information for a ultimate yes or no answer. To provide for decision making under these circumstances it is necessary to have a backup default strategy dictating the course of action. In summary form, the default decisions are shown in Figure E-2. This figure displays, for each of the decision questions, which answer must be chosen in case of uncertainty. In each case the default answer is based on protection of the equipment against serious consequences. This default approach can conceivably lead to more preventive maintenance than necessary. Some tasks will be included as protection against non-existent hazards and others may be scheduled too frequently. The means of eliminating excessive maintenance costs are provided by the age exploration studies which begin when the equipment goes into service. Through this process, the information needed to refine the initial RCM decisions and make necessary revisions is gathered systematically for evaluation.

**Kinds of preventive maintenance** RCM requirements consist of tasks selected on the basis of actual reliability characteristics of the equipment they are designed to protect. The tasks are one of two general types of preventive maintenance, either scheduled inspections or schedule removals. A scheduled inspection may be accomplished at any level of maintenance. It could be an inspection to detect impending failures or to detect functional failures which have occurred. Scheduled removals fall into two areas, removal for rework or reconditioning, or removal for throw away. Functional failures, reconditioning, and throw away tasks are directed at preventing single failures. Failure-finding tasks are directed at preventing multiple failures. The development of a preventive maintenance program consists of determining which of these four tasks, if any, are applicable and effective. Applicability depends on the failure characteristics of the item. An inspection for potential failures can be applicable only if an item has characteristics that define a potential failure condition. Similarly, an age limit task will be applicable only if the failures at which the task is directed are related to age. Effectiveness is a measure of the results of the task objective, which depends on the failure consequences involved. A proposed task might appear useful if it promises to reduce the overall failure rate; but it could not be considered effective if the purpose of applying it was to avoid all functional failures. A summary of applicability and effectiveness criteria for all tasks is provided by Figure E-3. For inspection tasks the distinction between applicability and effectiveness is usually obvious;

29 DEC 1987

## RCM DECISION LOGIC DIAGRAM

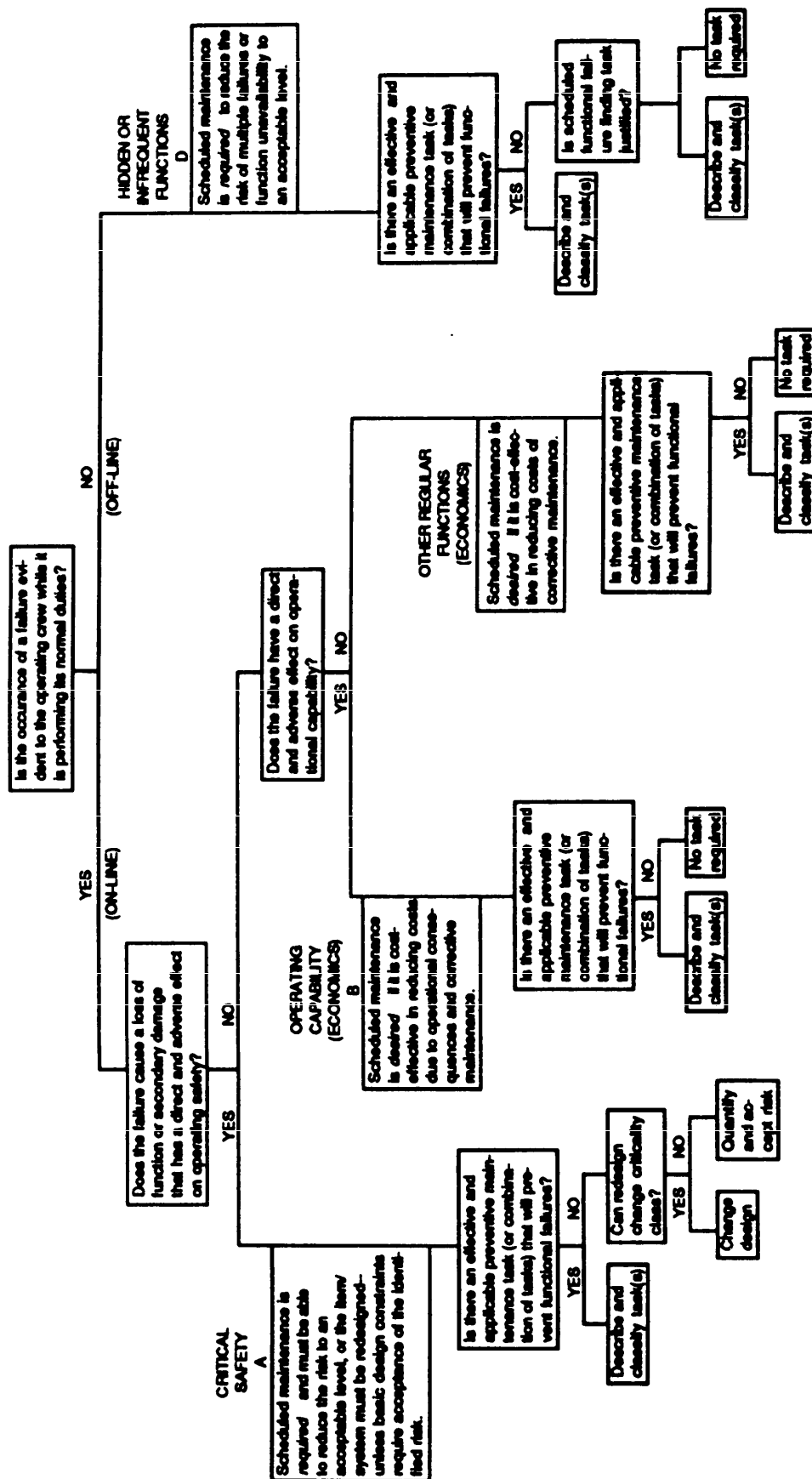


Figure E-1

Decision Question	(Stage At Which Question Can Be Answered)			Possible Adverse Consequences of Default Decision	Default Consequences Eliminated With Subsequent Operating Information
	Default Answer To Be Used In Case Of Uncertainty	Initial Program (With Default)	Ongoing Program (Operating Data)		
<b>IDENTIFICATION OF SIGNIFICANT ITEMS</b> Is the item clearly non-significant?	No: Classify item as significant.	X	X	Unnecessary analysis.	No
<b>EVALUATION OF FAILURE CONSEQUENCES</b> Is the occurrence of a failure evident to the operating crew during performance of normal duties?	No (except for critical secondary damage); classify function as hidden.	X	X	Unnecessary inspections that are not cost effective.	Yes
Does the failure cause a loss of function or secondary damage that could have direct adverse effect on operating safety?	Yes: Classify consequences as critical.	X	X	Unnecessary redesign or preventive maintenance that is not cost effective.	No for redesign; yes for preventive maintenance
Does the failure have a direct adverse effect on the operational capability?	Yes: Classify consequences as operational.	X	X	Preventive maintenance that is not cost effective.	Yes
<b>EVALUATION OF PROPOSED TASKS</b> Is an on-condition task to detect potential failures applicable?	Yes: Include on-condition tasks in program.	X	X	Preventive maintenance that is not cost effective.	Yes
Is an on-condition task applicable to make task effective?	Yes: Assign inspection intervals short enough to make task effective.	X	X	Preventive maintenance that is not cost effective.	Yes
Is a repair task to reduce the failure rate applicable?	No (unless there are real and applicable data); assign item to no preventive maintenance.	—	—	Delay in expediting opportunity to reduce costs.	Yes
Is a repair task applicable, is it effective?	No (unless there are real and applicable data); assign item to no preventive maintenance.	—	X	Unnecessary redesign (delay) or delay in expediting opportunity to reduce costs.	No for redesign; yes for preventive maintenance
Is a discard task to avoid failures or reduce the failure rate applicable?	No (except for safe life items); assign item to no preventive maintenance.	X (Safe life only)	X (Economic life)	Delay in expediting opportunity to reduce costs.	Yes
Is a discard task applicable, is it effective?	No (except for safe life items); assign item to no preventive maintenance.	X (Safe life only)	X (Economic life)	Delay in expediting opportunity to reduce costs.	Yes

THE DEFAULT ANSWERS TO BE USED IN DEVELOPING AN INITIAL PREVENTIVE MAINTENANCE PROGRAM IN THE ABSENCE OF DATA FROM ACTUAL OPERATING EXPERIENCE

Figure E-2: Default Decision Logic Chart

604-025

29 DEC 1987

## FAILURE CONSEQUENCES

<u>Task</u>	<u>Safety</u>	<u>Operational</u>	<u>Economic</u>	<u>Hidden Failure</u>
Effectiveness AI	Must reduce risk of failure to acceptable level.	Must be cost effective; cost of scheduled maintenance must be less than combined cost of loss of operation and repair.	Must be cost effective; cost of scheduled maintenance must be less than cost of repair.	Insure level of availability to reduce risk of multiple failure to acceptable level.
Applicability				
On Condition	1. Possible to detect reduced failure resistance. 2. Possible to define potential failure condition that can be detected by an explicit task. 3. Consistent age between potential failure and functional failure.	Same	Same	Same
Scheduled Rework	1. Identify age with rapid increase in conditional probability of failure. 2. Large percentage must survive to this age. 3. Possible to restore original failure resistance by rework.	Same	Same	Same
Scheduled Discard	1. Must be critical failure. 2. Specified age limit below which no failures occur.	1. Failure has major operational consequences. 2. Identify age with rapid increase in conditional probability of failure. 3. Large portion must survive to this age.	Same as operational	1. Must be critical multiple failure. 2. Specified age limit below which no failure occurs.
Failure Finding				1. Must be a hidden function. 2. No other task is applicable or effective.

Figure E-3: Applicability and Effectiveness Criteria Summary

29 DEC 1987

the item does not have characteristics that make such a task applicable. For age limit tasks, the distinction is sometimes blurred by the intuitive belief that the task is always applicable, therefore effective. In reality, imposing an age limit on an item does not guarantee that its failure rate will be reduced. The issue is not whether the task can be done, but whether doing it will enable the item to achieve its inherent reliability.

**Scheduled on-condition tasks** Scheduled inspections to detect potential failures are termed on-condition tasks, since they call for the removal or repair of individual units of an item "on the condition" that they do not meet the required standard. These tasks are directed at specific failure modes and are based on the feasibility of defining some identifiable physical evidence of a reduced resistance to the type of failure in question. Each unit is inspected at regular intervals and remains in service until its failure resistance falls below a defined level, that is, until a potential failure is discovered. Since on-condition tasks discriminate between units that require corrective maintenance to forestall a functional failure, and those units that will probably survive to the next inspection, they permit all units of the item to realize most of their useful lives. Many routine servicing tasks, such as checking oil quantity and air pressure, are on-condition tasks. The applicability of an on-condition task depends on both maintenance technology and the design of the equipment. For example, borescope and radioisotope techniques have been developed for inspecting turbine engines, but these techniques are of value chiefly because the engines have been designed to facilitate their use. Whenever an on-condition task is applicable, it is the most desirable type of preventive maintenance. It avoids the premature removal of units that are still in satisfactory condition, and the cost of correcting potential failures is often far less than the cost of correcting functional failures, especially those that cause extensive secondary damage. For this reason, on-condition inspection tasks are steadily replacing older practices.

**Scheduled rework tasks** Many single-celled and simple items display wearout characteristics - that is, the probability of their failure becomes significantly greater after a certain operating age. When an item does not have an identifiable wearout age, its overall failure rate can sometimes be reduced by imposing a hard time limit on all units to prevent operation at the ages of higher failure frequency. If the item's original failure resistance can be restored by rework or remanufacture, the necessary rework task may be scheduled at appropriate intervals. For example, an aircraft tire could have been scheduled for rework after a specified number of landings, since retreading restores the original failure resistance. However, this would have resulted in the retreading of all tires at the specified age limit, whether they needed it or not, and would not have prevented functional failures in those tires that failed earlier than anticipated. A rework task may be applicable, either for a simple item or to control a specific failure mode in a complex item. Although the age limit will be wasteful for some units and ineffective for others, the net effect on the entire population of that item will be favorable. This does not apply to complete rework of a complex item. Failures in complex items are the result of many different failure modes, each of which may occur at a different average age. Consequently, the overall failure rate of such items remains relatively constant. In some cases reliability decreases gradually with age, but there is no particular age that can be identified as a wearout zone. Unless there is a dominant wearout failure mode which is eliminated in the course of rework, complete rework of a complex item will have little or no effect on the overall failure rate.

**Scheduled discard tasks** The scheduled rework of items at a specified age limit is one type of hard time task. The other is scheduled discard of items or their parts at some specified operating age. Such tasks are frequently termed life limit tasks. Life limits may be established to avoid critical failures, in which case they are called safe life limits. They may also be established because they are cost effective in preventing noncritical failures, in which case they are called economic life limits.

29 DEC 1987

**Safe life limits** A safe life limit is imposed on an item only when safety is involved and there is no observable condition that can be defined as a potential failure. The item is removed at or before the specified maximum age and is either discarded or disassembled for discard of a specific part. This practice is most useful for simple items or individual parts of complex items such as pyrotechnic devices in ejection seats (which have a limited shelf life), or turbine engine disks and nonredundant structural members (which are subject to metal fatigue). The safe life limit is usually established by the equipment manufacturer on the basis of developmental testing. Initially, a component whose failure would be critical is designed to have an extensive life. It is then tested in a simulated operating environment to determine what average life has actually been achieved, and a conservatively safe fraction of this average life is used as the safe life limit.

**Economic life limits** Occasionally extensive operating experience may indicate that scheduled discard of an item is desirable on purely economic grounds. An economic life limit, however, is established in the same manner as an age limit for scheduled rework. It is based on the actual age/reliability relationship of the item, rather than on some fraction of the average age at failure. The objective of a safe life limit is to avoid accumulating any failure data. The only justification for an economic life limit is cost effectiveness. The failure rate must be known in order to predict how the total number of scheduled removals at various age limits would affect the cost benefit ratio.

**Scheduled failure finding tasks** A scheduled task may be necessary to protect the availability of a functional failure that is not evident to the operator. Hidden functional failures, by definition, have no immediate consequences, yet undetected failures increase the risk of multiple failures. If no other type of maintenance task is applicable and effective, hidden function items are assigned scheduled inspections for hidden failures. Although such tasks are intended to locate functional failures rather than potential failures, they can be viewed as a type of on-condition maintenance, since the failure of a hidden function item can also be viewed as a potential multiple failure. The chief difference is in the level of item considered; a functional failure of one item may be only a potential failure for the equipment as a whole.

**Age exploration program** Any preventive maintenance program can be developed and implemented with incomplete information. Generally there is limited data on the variation of failure resistance with age, variation of conditional probability of failure with age and the operational values of failure symptoms. An important element of RCM is age exploration - a procedure for systematically gathering the information necessary to determine the applicability and effectiveness of particular maintenance tasks. As this information accumulates, the RCM decision diagram provides a means of revising and refining the initial program. Much of this information is already available for equipment that has been in service for some time, although the specific data needed may have to be retrieved from several different information systems. The remaining useful life of the equipment will be a factor in certain decisions. RCM analysis under these circumstances will result in fewer default decisions and more efficient preventive maintenance requirements. Such programs usually include more maintenance requirements and usually include a larger number of on-condition inspections than a program arrived at under other policies, and fewer of the scheduled rework tasks. Age exploration is an integral part of the RCM program, and consists of two parts: (1) to detect decreases in reliability; and (2) to validate or determine the criteria for applicability and effectiveness of the four basic preventive maintenance tasks. Decreases in reliability can be detected through examination of in-service equipment to determine if the degradation is caused by increases in the rates of known failure modes or failure modes not anticipated. Data to support this part of age exploration can be found in the 3M data system and from engineering investigations, depot maintenance data, and

29 DEC 1987

operator discrepancy reports. The determination or validation of applicability and effectiveness criteria, the second part of age exploration, almost always requires special data collection programs. Since extra data collection imposes a greater workload on maintenance organizations, only essential data should be required and only for a period long enough to establish or validate the uncertain parameters.

### ANALYSIS OF CORRECTIVE MAINTENANCE

**Objective** The purpose of corrective maintenance trade-off analysis is to optimize repair characteristics associated with hardware at all levels of indenture, from system to component. Optimization of repair characteristics is usually accomplished by the following three methods:

1. Reduce the amount of down time that results from repair actions. The reduction of unscheduled maintenance downtime is a significant consideration, not only for  $A_0$  but also to increase the probability of mission success by restoring a failed item. The cost of corrective maintenance is measured by reduction in availability of the system and by the support resources required to restore the system to a specified level of operation.
2. Simplify maintenance procedures by designing for ease in performing the interchange of parts and to minimize the complexity of diagnosis, both of which can reduce skill and training level requirements for maintenance personnel. Simplified maintenance may also reduce numerical values for MTTR and maintenance man hours per operating hour. This objective serves to create an atmosphere in which maintenance work can be accomplished with greater reliability and accuracy.
3. Design for an optimum mix of spare parts for unscheduled organizational repairs. The range of design options can be illustrated with a description of the two extreme choices for maintenance at the operational site. The first design choice is replacement of the entire subsystem or major equipment item upon failure. This choice requires full redundancy of each sub-system and is usually prohibitive in terms of resources available. The other extreme design method is the capability to pinpoint and replace the exact source of every failure at the operational site. This choice is usually prohibitive in both excessive downtime of the subsystem and overall support cost.

**Repair Maintainability Design Techniques** There are a number of design techniques which may be implemented to improve the repair maintainability characteristics of equipment. These techniques may be described in three general categories:

1. **Equipment configuration methods** such as standardization, accessibility, modularity, unitization, and interchangeability are well established methods for reducing maintenance time. Standardization reduces waiting time for parts by decreasing the variety of parts which must be produced, stored, and shipped. Accessibility decreases both corrective and preventive maintenance time by allowing failure parts to be accessed more quickly. Modularity, unitization, and interchangeability decrease the number and type of assemblies that are diagnosed, removed, and replaced. Other configuration techniques include the design and location of controls, displays, inspection points, and lubrication points. Packaging and structure design also have significant impact on maintainability.

29 DEC 1987

2. Maintenance concepts and methods are another aspect of maintainability design. These techniques include modular replacement, automatic reconfiguration, remove and discard, and interchangeability.
3. Test and diagnosis are an important aspect of maintainability. Before repair can begin, the part of the equipment that has failed must be identified. As part of the diagnosis, test points will usually need to be used. If testability is designed into the item, then diagnosis will be quicker and more efficient. The concept of Built-In Test Equipment (BITE) and Automatic Test Equipment (ATE) make diagnosis easier.

Repair Maintainability Procedures MIL-STD-470A contains a number of specific tasks for maintainability, including program management, design and analysis, and test activities. Figure E-4 presents the matrix of the basic maintainability program tasks from MIL-STD-470A.

The task of modeling, allocation, and prediction are analytical techniques that allow the engineer to simulate the maintainability characteristics of equipment in order to determine sub-system requirements and to evaluate design progress. Operational requirements are translated into design goals through the use of modeling. An allocation and prediction can then be performed to optimize maintainability characteristics under given constraints. Maintainability models are used to determine the effect that a change in one variable has on system cost, maintainability, or maintenance performance characteristics. The models should relate to, or be consistent with, cost and system readiness models and other appropriate logistic support models. They may be utilized to determine the impacts of change in fault detection probability, proportion of failure isolation, frequency of failure, critical percentile to repair, or maintenance hours per flying or operating hour.

Maintainability allocation follows a process very similar to that of reliability allocation. The reliability allocation involves the establishment of MTBF design goals for the various sub-elements of the system. Maintainability allocation is a method of apportioning the system MTTR requirement to all of the functional sub-elements of the system. The maintainability allocation is performed after the reliability allocation and prediction because it requires estimates of subsystem or equipment failure rates that are the logical result of the reliability analysis. To start the process, the engineer must make rough estimates of subsystem or equipment MTTR values. These estimates or rough predictions, often must be obtained from the engineer's subjective judgements that are based on the maintenance concept, the diagnostic capabilities, and all interfacing logistic policies. Once these estimates have been made, the procedure is rather simple to determine whether or not the system MTTR requirement can be met.

Although the modeling and allocation techniques for maintainability are similar to the reliability engineering techniques, the prediction process for maintainability is quite different. Reliability engineering and prediction is a scientific technique through which the engineer can apply general engineering principles and good design practices to establish and assess the inherent failure rate. Maintainability however, is more of an art than a science. An individual's talent and experience are often more valuable than established principles. For example, the primary document for maintainability prediction procedures, MIL-HDBK-472, only provides techniques through which the analyst can summarize and average the estimated times for elementary maintenance tasks. The derivation of task time estimates is left to the analyst. The procedures of MIL-HDBK-472 can be applied only to electronic equipments which employ modular replacement.

29 DEC 1987

TASK NUMBER	TASK TITLE	TASK TYPE	PROGRAM PHASE				
			CON- CEPT	D+V	FSD	PROD	OPERATE SYSTEM DEVELOP (MODS)
101	Maintainability program plan	MGT	NA	G(3)	G	G(3) (1)	G(1)
102	Monitor/control of sub-contractors and vendors	MGT	NA	S	G	G	S
103	Program reviews	MGT	S	G(3)	G	G	S
104	Data collection, analysis and corrective action system	ENG	NA	S	G	G	S
201	Maintainability modeling	ENG	S	S(4)	G	C	NA
202	Maintainability allocations	ACC	S	S(4)	G	C	S(4)
203	Maintainability predictions	ACC	NA	S(2)	G(2)	C	S(2)
204	Failure modes and effects analysis (FMEA) maintainability information	ENG	NA	S(2) (3)(4)	G(1) (2)	C(1) (2)	S(2)
205	Maintainability analysis	ENG	S(3)	G(3)	G(1)	C(1)	S
206	Maintainability design criteria	ENG	NA	S(3)	G	C	S
207	Preparation of inputs to detailed maintenance plan and logistic support analysis (LSA)	ACC	NA	S(2) (3)	G(2)	C(2)	S
301	Maintainability demonstration (MD)	ACC	NA	S(2)	G(2)	C(2)	S(2)

**CODE DEFINITIONS:****PROGRAM PHASE**

S - Selectively applicable  
 G - Generally applicable  
 C - Generally applicable to design changes only  
 NA - Not applicable

**TASK TYPE**

ACC - Maintainability accounting  
 ENG - Maintainability engineering  
 MGT - Management

- (1) Requires considerable interpretation of intent to be cost effective
- (2) MIL-STD-470 is not the primary implementation document. Other MIL-STDs or Statement of Work requirements must be included to define or rescind the requirements. For example MIL-STD-471 must be imposed to describe maintainability demonstration details and methods.
- (3) Appropriate for those task elements suitable to definition during phase.
- (4) Depends on physical complexity of the system unit being procured, its packaging and its overall maintenance policy.

**Figure E-4: Maintainability Task Application Matrix**

29 DEC 1987

The Program Manager should be aware that the most practical means of assuring consideration in the design process of all qualitative factors that influence maintainability design, is to establish a dialogue between experienced maintenance and logistic specialists, and the design engineers. The most effective methods of formally implementing the required dialogue are design reviews, maintenance engineering checklists, and FMECA.

Maintainability design reviews provide an excellent means of exchange and evaluation of information related to both the design and maintenance of equipment. Early in the design state, equipment configuration may be adjusted to allow achievement of performance and reliability objectives and also to evaluate reliability/maintainability trade-offs. Maintainability design reviews may be conducted separately from formal program reviews in order to allow full attention to maintainability design without being overshadowed by concerns of schedule, budget, or other program requirements.

Maintainability design checklists are utilized throughout the design process to help the analyst think systematically and ensure consideration of the minimum design requirements. Checklists are developed by the maintenance specialist to describe to the equipment designer specific design features such as quick-release fasteners and self-alignment bearings. Checklists are most useful if they are tailored to the specific equipment and its general maintainability design.

The FMECA provides an excellent source of information for maintainability analyses and trade-off. It also provides a formal means of information transfer between the maintenance specialist, the design engineer, and the reliability engineer/analyst. The maintenance specialist may utilize the FMECA to identify failure modes with the associated maintenance tasks, both preventive and corrective. The FMECA allows tracking of the effects of maintenance actions. It will then directly correlate maintenance with systematic failure ranking of the criticality of maintenance actions for proper management of design changes.

#### **MAINTAINABILITY/SUPPORTABILITY TRADE-OFF ANALYSES**

**Logistic Support Analysis (LSA) and the Logistic Support Analysis Record (LSAR)**  
Evaluation of the supportability characteristics of a system design must consider all elements of the integrated logistic support (ILS) system:

- Maintenance
- Manpower and Personnel
- Supply Support
- Support Equipment
- Technical Data
- Training and Training Support
- Computer Resources Support
- Facilities

29 DEC 1987

- Packaging, Handling, Storage and Transportation
- Design Interface.

The maintenance characteristics of a system design may impact all of these ILS elements. Therefore, maintainability/supportability trade-off analyses require an analysis procedure which will consider and provide data on all the ILS elements. The LSA, defined and implemented through MIL-STD-1388, (Volumes 1 and 2) is the standard procedure for evaluation of the ILS elements of a weapons system. The LSA is comprised of a series of separate systems engineering analyses, or tasks, which may be performed on a selective basis to evaluate the impact of design decisions on the supportability of the system. Table E-1 presents the individual tasks which are incorporated in MIL-STD-1388-1A. These standardized tasks are structured for early design analysis of a system. Implementation of the ILS process is intended to provide the data through which design decisions can be made to balance system cost, schedule, performance, and supportability. MIL-STD-1388-1A provides general requirements and descriptions of tasks which, when performed in a logical and iterative nature, comprise the LSA process. The tasks are structured for maximum flexibility in application. In addition to the general requirements and task description section, the standard contains an application guidance appendix which may be utilized by the Program Manager for selection and tailoring of the tasks to meet program objectives in a cost-effective manner. The document is intentionally structured to discourage indiscriminate blanket applications. Tailoring is forced by requiring that specific tasks be selected and that certain essential information be provided by the Program Manager, relative to implementation of the selected tasks.

LSA documentation, including the LSAR, is generated as a result of the analysis tasks specified in MIL-STD-1388-1A. As such, the LSAR data serves as the integrated logistic support technical data base applicable to the analysis and design of support for a specific system through proper tailoring. The LSA performed per MIL-STD-1388-2A, establishes data element definitions, data field lengths, and data formats.

The specific data entry media, storage, and maintenance procedures are left to the discretion of the performing activity. A Standard Joint Service LSAR ADP system is available for automated storage of the LSAR data.

The LSAR forms a data base which may be utilized to:

- Determine the impact of design features on logistic support
- Determine the impact of the proposed logistic support systems on the system/equipment availability and maintainability goals
- Provide data for trade-offs studies, life cycle costing, and logistic support modeling
- Exchange data among functional organizations
- Influence the system/equipment design
- Provide data for the preparation of logistic products specified by data item descriptions (DID's)
- Provide the means to assess supportability of the fielded item

29 DEC 1987

Table E-1: Index of Logistic Support Analysis Tasks

TASK SECTION	PURPOSE OF TASK SECTION	TASK/SUBTASK	INFLUENCE.		
			SYS/EQUIP DESIGN	SUPPT SYS DESIGN	LOG REGMTS DETERMINATION
100 - PROGRAM PLANNING AND CONTROL	TO PROVIDE FOR FORMAL PROGRAM PLANNING AND REVIEW ACTIONS	101 - DEVELOPMENT OF AN EARLY LOGISTIC SUPPORT ANALYSIS STRATEGY  101.2.1 LSA STRATEGY 101.2.2 - UPDATES  102 - LOGISTIC SUPPORT ANALYSIS PLAN 102.2.1 - LSA PLAN 102.2.2 - UPDATES  103 - PROGRAM AND DESIGN REVIEWS 103.2.1 - ESTABLISH REVIEW PROCEDURES 103.2.2 - DESIGN REVIEWS 103.2.3 - PROGRAM REVIEWS 103.2.4 - LSA REVIEW			PRIMARY PURPOSE OF 100 SERIES TASKS IS THE MANAGEMENT AND CONTROL OF THE LSA PROGRAM
		201 - USE STUDY 201.2.1 - SUPPORTABILITY FACTORS 201.2.2 - QUANTITATIVE FACTORS 201.2.3 - FIELD VISITS 201.2.4 - USE STUDY REPORT AND UPDATES  202 - MISSION HARDWARE, SOFTWARE, AND SUPPORT SYSTEM STANDARDIZATION 202.2.1 - SUPPORTABILITY CONSTRAINTS 202.2.2 - SUPPORTABILITY CHARACTERISTICS 202.2.3 - RECOMMENDED APPROACHES 202.2.4 - RISKS	X X X X  X X X X	X X X X  X X X X	X       X  X X
200 - MISSION AND SUPPORT SYSTEMS DEFINITION	TO ESTABLISH SUPPORTABILITY OBJECTIVES AND SUPPORTABILITY RELATED DESIGN GOALS, THRESHOLDS, AND CONSTRAINTS THROUGH COMPARISON WITH EXISTING SYSTEMS AND ANALYSES OF SUPPORTABILITY, COST, AND READINESS DRIVERS				
			• X INDICATES THAT THE SUBTASK IS ORIENTED TOWARD INFLUENCING THE INDICATED FACTOR(S).		

**Table E-1: Index of Logistic Support Analysis Tasks – Continued**

TASK SECTION	PURPOSE OF TASK SECTION	TASK/SUBTASK	INFLUENCE.			LOG REGRTS DETERMINATION
			SYS/EQUIP DESIGN	SUPPT SYS DESIGN		
		203 - COMPARATIVE ANALYSIS 203.2.1 - IDENTIFY COMPARATIVE SYSTEMS 203.2.2 - BASELINE COMPARISON SYSTEM 203.2.3 - COMPARATIVE SYSTEM CHARACTERISTICS 203.2.4 - QUALITATIVE SUPPORTABILITY PROBLEMS 203.2.5 - SUPPORTABILITY, COST, AND READINESS DRIVERS 203.2.6 - UNIQUE SYSTEM DRIVERS 203.2.7 - UPDATES 203.2.8 - RISKS AND ASSUMPTIONS	X X X X X X X X	X X X X X X X X		
		204 - TECHNOLOGICAL OPPORTUNITIES 204.2.1 - RECOMMENDED DESIGN OBJECTIVES 204.2.2 - UPDATES 204.2.3 - RISKS	X X X	X X X		
		205 - SUPPORTABILITY AND SUPPORTABILITY RELATED DESIGN FACTORS 205.2.1 - SUPPORTABILITY CHARACTERISTICS 205.2.2 - SUPPORTABILITY OBJECTIVES AND ASSOCIATED RISKS 205.2.3 - SPECIFICATION REQUIREMENTS 205.2.4 - NATO CONSTRAINTS 205.2.5 - SUPPORTABILITY GOALS AND THRESHOLDS	X X X X	X X X X X		

29 DEC 1987

Table E-1: Index of Logistic Support Analysis Tasks - Continued

TASK SECTION	PURPOSE OF TASK SECTION	TASK/SUBTASK	INFLUENCE.		
			SYS/EQUIP DESIGN	SUPPT SYS DESIGN	LOG REGIMTS DETERMINATION
300 - PREPARATION AND EVALUATION OF ALTERNATIVES	TO OPTIMIZE THE SUPPORT SYSTEM FOR THE NEW ITEM AND TO DEVELOP A SYSTEM WHICH ACHIEVES THE BEST BALANCE BETWEEN COST, SCHEDULE, PERFORMANCE, AND SUPPORTABILITY	301 - FUNCTIONAL REQUIREMENTS IDENTIFICATION			
		301.2.1 FUNCTIONAL REQUIREMENTS		X	
		301.2.2 UNIQUE FUNCTIONAL REQUIREMENTS		X	
		301.2.3 RISKS		X	X
		301.2.4 OPERATIONS AND MAINTENANCE TASKS		X	
		301.2.5 DESIGN ALTERNATIVES		X	X
		301.2.6 UPDATES	X		
		302 - SUPPORT SYSTEM ALTERNATIVES			
		302.2.1 ALTERNATIVE SUPPORT CONCEPTS		X	
		302.2.2 SUPPORT CONCEPT UPDATES		X	
		302.2.3 ALTERNATIVE SUPPORT PLANS		X	
		302.2.4 SUPPORT PLAN UPDATES		X	
		302.2.5 RISKS		X	
		303 - EVALUATION OF ALTERNATIVES AND TRADE-OFF ANALYSIS			
		303.2.1 TRADEOFF CRITERIA	X	X	X
		303.2.2 SUPPORT SYSTEM TRADEOFFS	X	X	X
		303.2.3 SYSTEM TRADEOFFS	X	X	X
		303.2.4 READINESS SENSITIVITIES	X	X	X
		303.2.5 MANPOWER AND PERSONNEL TRADEOFFS	X	X	X
		303.2.6 TRAINING TRADEOFFS	X	X	X
		303.2.7 REPAIR LEVEL ANALYSES	X	X	X
		303.2.8 DIAGNOSTIC TRADEOFFS	X	X	X
		303.2.9 COMPARATIVE EVALUATIONS	X	X	X
		303.2.10 ENERGY TRADEOFFS	X	X	X
		303.2.11 SURVIVABILITY TRADEOFFS	X	X	X
		303.2.12 TRANSPORTABILITY TRADEOFFS	X	X	X

29 DEC 1987

Table E-1: Index of Logistic Support Analysis Tasks - Continued

TASK SECTION	PURPOSE OF TASK SECTION	TASK/SUBTASK	INFLUENCE		
			SYS/EQUIP DESIGN	SUPPT SYS DESIGN	LOG REQMTS DETERMINATION
400 - DETERMINATION OF LOGISTIC SUPPORT RESOURCE REQUIREMENTS	TO IDENTIFY THE LOGISTIC SUPPORT RESOURCE REQUIREMENTS OF THE NEW SYSTEM IN ITS OPERATIONAL ENVIRONMENT(S) AND TO DEVELOP PLANS FOR POST PRODUCTION SUPPORT	401 - TASK ANALYSIS			X
		401.2.1 TASK ANALYSIS			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	401.2.2 ANALYSIS DOCUMENTATION			X
		401.2.3 NEW/CRITICAL SUPPORT RESOURCES			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	401.2.4 TRAINING REQUIREMENTS AND RECOMMENDATIONS			X
		401.2.5 DESIGN IMPROVEMENTS			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	401.2.6 MANAGEMENT PLANS			X
		401.2.7 TRANSPORTABILITY ANALYSIS			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	401.2.8 PROVISIONING REQUIREMENTS			X
		401.2.9 VALIDATION			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	401.2.10 ILS OUTPUT PRODUCTS			X
		401.2.11 LSAR UPDATES			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	402 - EARLY FIELDING ANALYSIS			X
		402.2.1 NEW SYSTEM IMPACT			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	402.2.2 SOURCES OF MANPOWER AND PERSONNEL SKILLS			X
		402.2.3 IMPACT OF RESOURCE SHORTFALLS			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	402.2.4 COMBAT RESOURCE REQUIREMENTS			X
		402.2.5 PLANS FOR PROBLEM RESOLUTION			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	403 - POST PRODUCTION SUPPORT ANALYSIS			X
		403.2 POST PRODUCTION SUPPORT PLAN			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	501 - SUPPORTABILITY TEST, EVALUATION, AND VERIFICATION			X
		501.2.1 TEST AND EVALUATION STRATEGY			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	501.2.2 OBJECTIVES AND CRITERIA			X
		501.2.3 UPDATES AND CORRECTIVE ACTIONS			X
500 - SUPPORTABILITY ASSESSMENT	TO ASSURE THAT SPECIFIED REQUIREMENTS ARE ACHIEVED AND DEFICIENCIES CORRECTED	501.2.4 SUPPORTABILITY ASSESSMENT PLAN (POST DEPLOYMENT)			X
		501.2.5 SUPPORTABILITY ASSESSMENT (POST DEPLOYMENT)			X

606-054

29 DEC 1987

- Provide the means to evaluate the impact of engineering change, product improvement, major modification, or alternative proposals.

As such, the LSAR is the data base which is utilized for maintainability/supportability trade-off design analyses.

**Level of Repair Analysis (LORA)** The LORA is a specialized maintainability/supportability trade-off design analysis. The LORA is intended to determine the optimum level of repair facility at which a maintenance action will be performed: organizational, intermediate, or depot facility. The LORA is performed in accordance with MIL-STD-1390, and utilizes standardized computer models and cost factors. The LSAR is a data base utilized in conducting the LORA. The maintainability design characteristics, utilized as inputs to the LORA, include maintenance procedures described in task, skills, and time line analyses. The following technical factors are presented as examples of the maintenance factors utilized in conducting a LORA:

- **Life cycle** The entry in this field is the total number of years (including the Base Year) that the equipment is operational and for which logistics support costs are to be calculated in deriving LORA recommendations
- **Gross Removal Factor (GRF)** Expected number of items removed from the next higher assembly, including false removals
- **Unit Cost** The estimated unit procurement cost of the item, in dollars and cents
- **MTBF** The predicted mean time between failures, in terms of operating hours
- **MTTR** The predicted mean time to repair the item, in elapsed hours. This factor is used to compute operational availability of the equipment and to provide estimates of maintenance shop workloads
- **Repair cycle** The average number of days required for shop repair. Separate entries are made for organizational, intermediate, and depot
- **Beyond Capability of Maintenance Rate** The percentage of failures that cannot be repaired at the indicated maintenance levels and are sent to a higher level maintenance activity for repair or condemnation. Separate entries are provided for organizational and intermediate level maintenance sites
- **Scrap Rates** Fractions of failures that cannot be repaired and are scrapped at the indicated maintenance level. Different values are used for organizational, intermediate, and depot level maintenance sites
- **False Removal Rates** Percentages which are multiplied by the number of real failures to give the number of false removals of the item. Different values are used for organizational, intermediate, and depot level maintenance sites
- **False Removal Detection Rates** Percentages which are multiplied by the number of false removals to give the number of such removals identified as

29 DEC 1987

false. Different values are used for organizational, intermediate, and depot level maintenance sites.

The basis for each of the technical factors is dependent upon the type of equipment (system or support equipment). The Program Support Inventory Control Point (PSICP), normally SPCC, Mechanicsburg, PA or ASO, Philadelphia, PA that will be supporting the item can normally provide approximations of these rates for similar existing items.

The LORA is conducted as an integral part of the maintenance planning and analysis process. Level of repair models are analogous to the planned maintenance practices and procedures for the system. They provide an advanced look at intermediate and depot support costs. The Program Manager must ensure that LORAs do not result in uncoordinated changes to the logistic support analysis data base.

The LORA may be conducted as a computer-based model, or by manual computation for simple systems. If computer-based analysis is required, the contractor may request existing level of repair computer programs through the Program Manager. Subsequently, the designated activity will provide level of repair computer programs, user's guides, and other such program documentation that will enable the contractor to meet the processing requirements associated with MIL-STD-1390. The government will not provide computer capability to the contractor.

The Program Manager may also require level of repair analysis using non-economic factors, including safety, repair feasibility, and mission success. This analysis, if required, is accomplished without cost as the prime consideration, and is performed prior to the LOR economic analysis. Any LOR recommendations based on non-economic analysis may also include an economic analysis in order to assign some economic value to the non-economic recommendation.

Additional data is developed in the analysis that is not a direct part of the LORA. The contractor uses data from LOR decisions, government furnished information, and the maintenance planning data (as adjusted), to select source, maintenance and recoverability (SM&R) codes for the items for which LOR analyses were conducted. In addition, the contractor uses the analytical data, the government furnished information, and maintenance planning data to compute the technical factors associated with maintenance plans, as specified in MIL-STD-1390.